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ABSTRACT

A study explored how untutored technology education students used three-dimensional modelling while designing and making a solution to a technological problem. A literature review focused on modelling as a design process skill and its purposes. Ten seventh-grade students (six boys and four girls) were paired into five single-sex dyads. Each dyad designed and made a solution to a common task: to construct the tallest possible tower. Successful completion of the task required engagement in the design process steps. Each design and make session was recorded on audio and videotape. Within 3 days, each dyad returned for a semistructured retrospective interview. Analysis involved transcribing and segmenting subjects' talk during the problem solving and interviews. Transcripts were segmented into "speech bursts" (defined as "a complete portion of text uttered by a subject without interruption from that subject's partner") and change in subjects' actions. Codes were designed to describe subjects' actions--the manifestations of their design thinking. Data analysis found five significant differences between the role of modelling as described in design process models and the subjects' strategies: (1) subjects used three-dimensional modelling largely to replace two-dimensional modeling; (2) subjects did not present several solutions at the outset; (3) subjects used three-dimensional modelling to fuel ideas for further cognitive modelling, which then needed to be tried out in concrete form; (4) modelling was used to develop and refine ideas; and (5) subjects repeatedly and constantly evaluated their models. (Contains 25 references) (YLB)

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Thinking With the Hands: Students' Use of Three-Dimensional Modelling While Designing and Making

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Introduction

Thinking with the hands (Thring, 1977), that is, modelling ideas as drawings or three-dimensional representations, is an essential component of designing and making. As McKim (1980) has described, visual thinking is greatly facilitated by modelling in all its forms. Yet little is known about the most effective way to teach students to represent their mental images in concrete form. Certainly, when left to their own devices in an environment rich in three-dimensional materials, students of all ages frequently design and make unique and creative solutions to a technological problem. However, the modelling strategies they use appear to conflict with those described in design process models found in technology education textbooks and curricula. To date, little research has investigated the actual practice of untutored designers to confirm or deny empirically the existence of this apparent conflict.

The purpose of this paper is to describe how untutored technology education students use three-dimensional modelling while designing and making a solution to a technological problem. The paper is part of a larger study (Welch, 1996) that explored the conflict

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between the design strategies students bring to the classroom and those advocated in the technology education literature.

This paper begins with a review of the related literature. Next, the methodology developed to elicit, capture and analyze the modelling strategies used by subjects is described. This is followed by discussion of the way in which these strategies differ from those in theoretical models of the design process. The implications of these findings for the teaching of designing and making complete the paper.

Modelling as a Design Process Skill

Modelling in all its forms (two-dimensional, three-dimensional, symbolic, and computer) is an essential feature of designing and making (Murray, 1992; Smith, 1993). Ideas conceived in the mind need to be expressed in concrete form before they can be examined to see how useful they are. As Kimbell, Stables, Wheeler, Wosniak, and Kelly (1991) wrote, "it is [the] inter-relationship between modelling ideas in the mind, and modelling ideas in reality [that] is the cornerstone of capability in ... technology education" (p. 21).

In the context of technology education the term 'modelling' includes modelling inside the head, that is, cognitive modelling or imaging, and modelling outside the head, that is, concrete modelling (Kimbell et al. 1991; Murray, 1992). According to Murray "modelling inside the head includes the activities of imaging thoughts and ideas and shaping and forming those ideas using images and representational forms" (p. 37).

Four types of concrete modelling are generally available to students: two–dimensional, three–dimensional, symbolic, and computer (Barlex, 1994; Evans, 1992; Harrison, 1992; Sparkes, 1993). Two–dimensional modelling involves making representations of design ideas on paper. Techniques include rough sketches, annotated diagrams, exploded diagrams, renderings, and engineering drawings (Barlex, 1994; Johnsey, 1995). Three–dimensional modelling involves the use of construction techniques leading to "the fabrication of a form occupying space" (Harrison, 1992, p. 33). Resources may include easily worked materials such as paper, card, foam core, straws and coffee stirrers. Kits such as Lego can be used to explore mechanisms and structures. Symbolic modelling uses a symbol to represent an object. For example, mathematical formulae, calculations and graphs may be used to calculate bending moments in structures. Standard symbols may be used to represent, for example, components in a circuit diagram. Computer modelling may be used to explore the form of an object (3D modellers), to animate a mechanism (animation programmes), to explore a variety of finishes (paint programmes) and, using CAD software, generate working drawings (Barlex, 1994). Computer modelling may also be used to apply mathematical functions to data arranged in a spreadsheet, which can, in turn, be used to model economic and technical aspects of a technology (Harrison, 1992).

The Purposes of Modelling

Modelling may serve the purposes of both the student and the teacher. For the student, modelling serves to visualise the whole or component parts of the product and its finished appearance, identify possible faults in a design, frame ideas, test the performance of a

mechanism or circuit, examine the relationship of components, improve the form of the product, identify the properties and working constraints of materials, communicate ideas and information to others, and evaluate ideas (Davies, 1996; Evans & Wormald, 1993; Liddament, 1993; Sparkes, 1993).

For the teacher modelling serves a quite different purpose. Murray (1992) suggests that teachers should use a student's "modelling ... [as] evidence of the conceptual modelling that the student has engaged in" (p. 39). But as Barlex (1994) warns

> It is all too easy to see the end result ... 'the models', as the most significant part of the activity. They are only significant ... [in that] they reveal ... the mental processes of the pupil in coming to grips with the design task .... It is important ... to see them for what they are ... insights into pupil thinking. (p.79)

Given that modelling is a process skill essential to students' success when designing and making, how can it best be taught? What specific skills and knowledge are required? What materials should be provided? How do teachers help students express ideas? Because of its relatively recent introduction into the school curriculum, technology education has but a limited corpus of empirically derived research findings to answer such questions. The next section of this paper describes a methodology developed to investigate the modelling strategies used by untutored students.

Methodology

Ten Grade 7 students (six boys and four girls) were paired into five single-sex dyads. Because the research design followed a multiple-case study logic it was critical to ensure that each dyad designed and made a solution to a common task. Therefore each dyad was provided with a copy of the following design brief:

> Using ONE sheet of 220 mm x 280 mm white paper and 100 mm of clear tape, construct the tallest possible tower.
>
> You will also be given pink paper. This you may use in any way as you develop your solution. However, NONE of the pink paper may be used in the tower you submit as a final product.
>
> Limitations:
>
> There is a time limit of one hour.
>
> The tower must be free standing. It cannot be taped to the floor nor to anything else.
>
> When you have finished, the tower must stand for 30 seconds before having its height measured.

This particular task was selected for five reasons. First, it contains the three elements which Cross (1994) describes as common to all design problems: "(a) a goal, (b) some constraints within which the goal must be achieved, and (c) some criteria by which a successful solution might be recognized" (p. 10). Second, successful completion of the task requires engagement in the following design process steps; understanding the

problem, generating possible solutions, modelling a solution, building a solution, and evaluating a solution. Third, informal pilot testing in a variety of educational settings over a number of years by the researcher has demonstrated the task to be one which students enjoy. Fourth, the task does not require any equipment or skills beyond the abilities of Grade 7 students who have received no formal technology education. Finally, the task does not involve the use of dangerous equipment or materials.

Each design and make session was audio and video recorded. Subjects were encouraged to talk normally during the session. Within three days each dyad returned for a semi-structured retrospective interview, during which subjects watched the video of their problem-solving session

Analysis involved transcribing and segmenting subjects' talk during both the problem-solving session and the retrospective interviews. In this study transcripts of the design and make session were first segmented into "speech bursts" (Miles & Huberman, 1994, p. 56), defined as "a complete portion of text uttered by a subject without interruption from that subject's partner". Each speech burst was typed on a new line, with the speaker identified by a code name. The start time, in minutes and seconds, of each segment was added. Finally, a description of the subjects' actions was included to the right of each segment. Transcripts were then segmented a second time, each new segment delimited by a change in the actions of the subjects.

A coding scheme was developed to reflect the problem-solving nature of designing as described in the technology education and human problem solving literature (Department for Education, 1995; Newell & Simon, 1972; Kimbell, et al. 1991). Codes were designed to describe the actions of the subjects, that is, the manifestations of their design thinking.

The final step in the analysis required the production of a series of empirical maps depicting the design process used by each of the dyads, and then the comparison of these to a theoretical design process. Such maps make it possible to search for patterns in a single data set and for regularities in multiple data sets.

Results

Analysis of the data made evident five significant differences between the role of modelling as described in design process models and the untutored strategies of subjects (Figure 1 is representative of the map generated for each dyad).

FIGURE 1 HERE

Figure 1. The strategy used by Dyad 5

First, subjects used three-dimensional modelling to largely replace two-dimensional modelling. Generating possible solutions was accomplished not by sketching but by

modelling with three-dimensional materials. Indeed, the low importance given to sketching is emphasized by the actions of several subjects who, having made minor attempts at exploring their ideas on paper, promptly used the same piece of paper to model a solution. As one subject said "I started fooling around with the paper and I completely forgot about the drawing". In other words, subjects did not use 3-D modelling to further develop some "less-developed form", but rather to "originate [and] develop ... their ideas" (Evans & Wormald, 1993, p. 97).

Second, subjects did not present several solutions at the outset. They were more likely to develop solutions serially: an idea was generated, developed as a model, evaluated, and then abandoned. Subsequent solutions, sometimes although not always informed by experience and knowledge gained from previous models, were similarly developed.

Third, as Murray (1992) has also observed, subjects used three-dimensional modelling to fuel ideas for further cognitive modelling, which then needed to be tried out in concrete form. When Dyad 4 had successfully completed a tower made by cutting a sheet of paper into two equal parts, rolling and taping them into cylinders, and joining them end-to-end, S8 said "Okay, um, we could cut it [a sheet of paper] in three". It appears that simultaneously generating ideas and modelling with three-dimensional materials was an important aid to subjects' thinking about a solution.

Fourth, modelling was used not only to develop but also to refine ideas. For example, Dyad 1 had rolled and taped two identical cylinders and were about to make it stand. However, before this could occur S1 interrupted and said, "Let's cut the bottom out to make sure it stands". S2 then proceeded to cut and bend four tabs at the bottom edge of the tower in order to form a base.

Fifth, analysis showed that subjects were repeatedly and constantly evaluating their models from the first moment that making began. Testing during modelling often led to the identification of a design problem and suggested refinements. The data also suggest that evaluating led to the acquisition of knowledge which subsequently informed the design of the next solution.

Discussion

Subjects in this study used three-dimensional modelling in a number of ways: to increase understanding of the problem; to externalize a cognitive model; to transform a two-dimensional model into a three-dimensional form; to fuel ideas for further cognitive; and to test or evaluate a solution. This is perhaps no surprise, for as Hayes (1989) has written "much of our knowledge of solution strategies is acquired rather unsystematically through our daily experience in solving problems" (p. 52). The bulk of students' untutored technological problem-solving skill will have been acquired in the material world: building sand castles, using commercial construction kits, constructing with found materials, and so on.

This empirical explanation for a subject's preference for modelling ideas in three-dimensional materials is further supported by Piagetian learning theory. Piaget (1964) postulated that senior elementary school students think in terms of concrete, existing objects and are not yet able to use abstractions. Therefore, the requirement that students sketch several possible solutions, that is, work in an abstract form, before modelling in three-dimensional materials is not supported by developmental theory or by the results of this study. Rather, the results suggest that it may be important to provide students, early in the process, an opportunity to explore, develop and communicate their design proposals by modelling ideas in three-dimensional form. However, this may pose something of a difficulty, for as Hayes (1989) has identified, there are a number of disadvantages to working with three-dimensional materials prior to planning and exploring ideas using sketches.

Additionally, research has shown how students with no prior technology education do not have the skills to represent in two-dimensional form an object which will eventually be made using three-dimensional materials (Constable, 1994a). There is often a mismatch between students' imaginative abilities and their representational skills (Anning, 1993). Novice designers must be taught not only the skill of drawing, but also to use drawings as a way to record and explore, to think through, in an abstract way, their design ideas. At the same time, given the importance to subjects in this study of modelling in three-dimensional materials, teachers must think about the relationship between two-

dimensional and three-dimensional modelling and the difficulties that students appear to experience in making the transition between the two.

Subjects spent very little time planning prior to making a model. As Johnsey (1995) has also observed subjects were anxious to begin making even before they had clarified their ideas about what to make and how best this might be achieved. This led to a considerable amount of designing by trial-and-error. Yet as Harrison (1992) has pointed out "part of technological capability is being able to design in a predictive way, rather than by trial-and-error" (p. 35). The evidence from this study suggests that subjects did not have the skills or knowledge to enable predictive designing to take place. Harrison (1992) suggests that, "modelling in three-dimensions in a range of materials [may be] an important way to establish the skills which would, in the future, allow predictive designing" (p. 35). The richness of this experience for the student was described by Johnsey (1995) when he wrote "this early interaction with materials means the student is simultaneously researching the problem, generating solutions, learning tools skills and qualities of materials" (p. 19).

The data also suggest that seeing an idea translated into a three-dimensional model stimulates additional idea generation. When Dyad 4 have successfully completed a tower made by cutting a sheet of paper into two equal parts, rolling and taping them into cylinders, and joining them end-to-end, S8 says "Okay, um, we could cut it [a sheet of paper] in three" (lines 293-294).

Modelling also allowed subjects to refine ideas. For example, Dyad 1 had rolled and taped two identical cylinders and were about to make it stand. However, before this could occur S1 interrupted and said, "Let's cut the bottom out to make sure it stands" (lines 305-306). S2 then proceeded to cut and bend four tabs at the bottom edge of the tower in order to form a base.

Conclusion

This study has illustrated how three-dimensional modelling was used by untutored technology education students to support a range of activities: increasing understanding of the problem, stimulating the generation of solutions, seeing what a design would look like, testing, and continuously incorporating modifications and improvements into a solution. This is perhaps no surprise, for as Schön (1987) has written "designing is a creative activity. A designer's reflective conversation with the materials of a situation can yield new discoveries, meanings, and inventions" (p. 161). What remains to be explored are such questions as: What are the most appropriate skills to teach students in order to facilitate their ability to externalize ideas? At what stage in their development as designers can and should students be taught two- and three-dimensional modelling skills? How are these skills best taught? Which materials best support students' learning of modelling techniques? And, perhaps most importantly, what cognitive development occurs as a result of a student's engagement in the design process skill modelling?

2756 words

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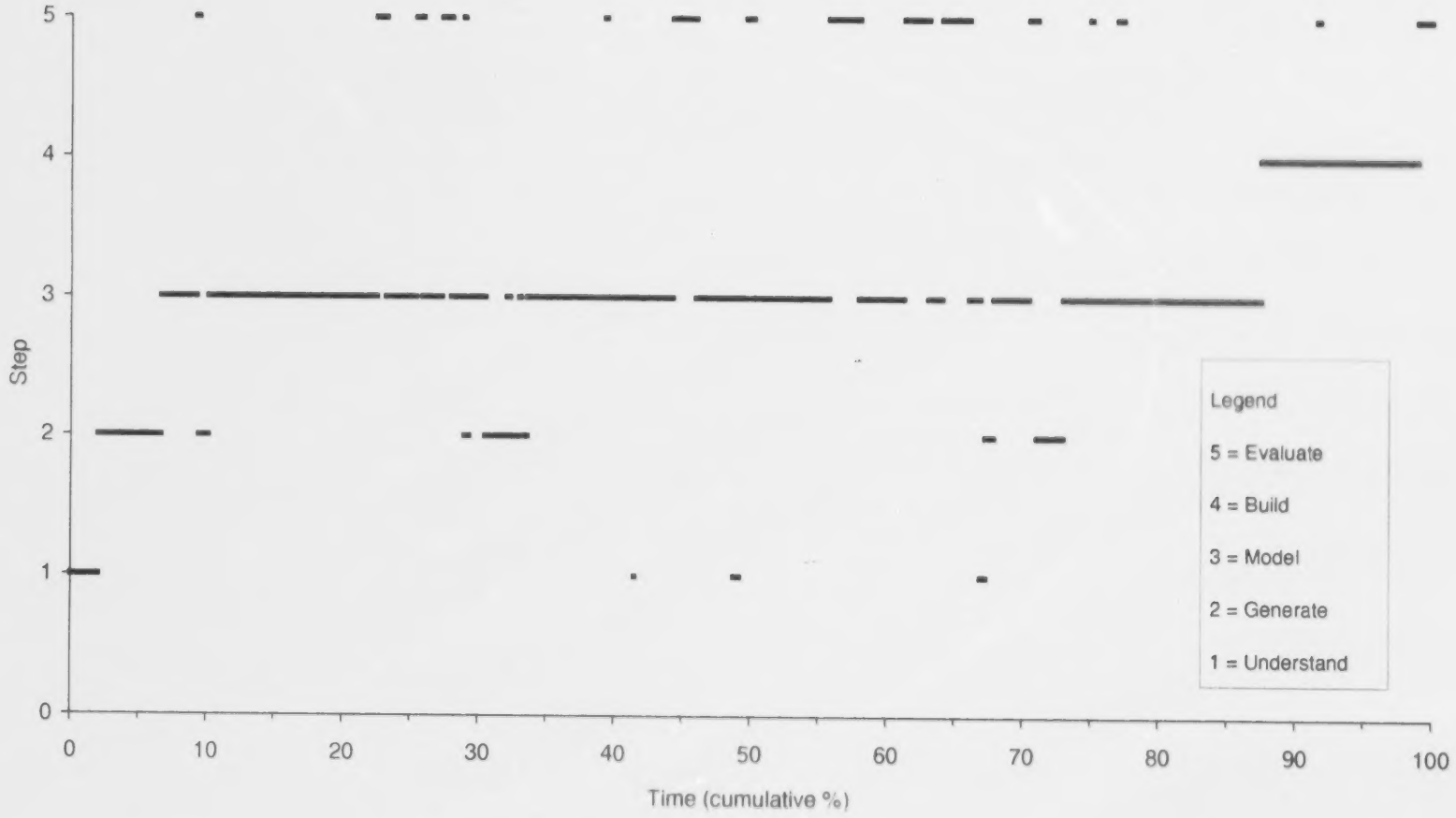
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Time (cumulative %)
Legend
5 = Evaluate
4 = Build
3 = Model
2 = Generate
1 = Understand